IX. *The Constitution of the Electric Spark.*

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[PLATES 28–29.]

1. *Previous Experiments.*—In the year 1899 Professor SCHUSTER and Dr. HEMSALECH* published the results of their experiments on the Constitution of the Electric Spark. On a slit parallel to the spark they formed an image of a spark produced between metal electrodes by a Wimshurst machine and photographed the light passing through the slit, both directly and after analysis by a prism, on a moving film in the focal plane of the camera lens, the direction of motion of the film being at right angles to the direction of the slit. A summary of their results is given below :—

(1.) In the photographs on the moving film the lines in the spectrum which are due to the metallic vapour were inclined, whilst the air lines were straight.

(2.) They regarded the inclination of the lines as an indication of the velocity of propagation of the metallic vapour, and did not discuss any possibilities of the propagation of luminosity through vapour which may be, as a whole, stationary.

(3.) Different lines in the spectrum had different inclinations. This was most marked in the bismuth spectrum.

(4.) The lighter metals had a greater velocity than the heavier metals.

(5.) The calcium lines H and K, due to impurities in the silver electrodes, became luminous first in the centre of the gap, and were propagated towards the electrodes.

(6.) Of the vibrations excited by the discharge those of some periods are intense and of short duration, whilst those of other periods are too faint to show in the moving photograph, but are visible in the stationary one because the vibration persists some time.

* SCHUSTER and HEMSALECH, 'Phil. Trans.,' A, vol. 193, p. 189 (1899).

2. *Aim of the Present Research.*—Professor SCHUSTER suggested that I should repeat and continue the experiments done by himself and Dr. HEMSALECH. It was hoped to obtain photographs with greater dispersion, greater resolving power, and improved definition, which would remove the doubts expressed by other observers regarding the interpretation of the photographs, and would elucidate still further the constitution of the spark.

3. *Apparatus Employed.*—The arrangement of the apparatus was substantially the same as that used by SCHUSTER and HEMSALECH, except that two prisms were used instead of one. The prisms, which were kindly lent by Dr. R. S. HUTTON for this research, had each an angle of 60 degrees and a base of 5 centims. The glass is a medium flint, of high transparency to the ultraviolet. The prisms were tested separately by observing the sodium D lines produced by a sodium bead in the Bunsen flame. The definition appeared to be perfect, and was not improved by allowing light to pass through only a narrow portion of the prism. With these prisms and the same lenses as were used in the previous work the extent of the spectrum from F to H is 2 centims.

The optical system was adjusted as described in the paper referred to, and the prisms placed in the position of minimum deviation for about λ 4200, the centre of the region to be photographed. The same method of focussing the spectrum on the photographic film has been adopted. The photographic film is carried on the same disc as used by the earlier experimenters, and can be rotated by a motor at speeds up to 160 revolutions per second. The speed of the disc is given by that of the motor read by a direct-reading speed-indicator by Elliot Bros., which has been tested and found accurate.

The sparks were obtained between metallic electrodes from a condenser charged by means of a large Wimshurst machine capable of producing, without condensers, sparks 12 inches long. The best form for the electrodes is conical. Their surfaces were prepared with fine emery cloth, and finally polished by rubbing with wash-leather to remove small projections which would cause preliminary discharges before the condensers were fully charged, or which might affect the results on account of the distribution of the electric force near them. This preparation of the electrodes, however, probably introduces the calcium lines H and K into the spectrum. The condensers consist of plates of glass coated with tinfoil, connected in parallel with each other. The total capacity is 0·0306 mfd. They could be divided so as to obtain capacities of 0·0206 and 0·0103 mfd., roughly two-thirds and one-third of the total capacity.

The improvement of the definition of the photographs reproduced in this paper over those of SCHUSTER and HEMSALECH is due to the improved optical quality of the prisms used and the greater care taken in preventing a backward or forward displacement of the rotating disc.

4. *Measurement of the Photographs.*—If both electrodes are of the same material,

so that the lines which appear at both the top and bottom of the spectrum can be measured and the means taken, SCHUSTER and HEMSALECH showed that the velocity of the vapour between two points is equal to

$$\mathrm{K}v\,\frac{y_2-y_1}{x_2-x_1},$$

where

K is the reciprocal of the magnification of the system (= 1·16);
v is the velocity of the film at the centre of the spectrum;
x_1, x_2, the co-ordinates of the points measured parallel to the spectrum;
y_1, y_2, the co-ordinates of the points measured at right angles to the spectrum.

Even if the line can only be measured at either the top or the bottom, this expression may generally still be used, the differences from the more accurate one being less than the errors of experiment. If, however, it should be required to calculate velocities from the more accurate formula of SCHUSTER and HEMSALECH, it will be necessary to know the distance of any line in the spectrum from a vertical through the centre of the disc. This has been obtained by measuring on the disc itself the distance of a vertical through the centre of the disc from where the air line λ 5004 falls on the disc. From this, the distance for any line in the spectrum can be found.

Method of Making the Measurements.—A number of fine lines were drawn parallel to each other, at equal distances of about 8 millims., on a sheet of paper, and reduced to the necessary size by photographing on a glass plate. In this way rulings have been made whose spaces were 0·0503 centim. and 0·0200 centim.

The photograph of the spectrum was placed flat on the ruling with the two emulsions together, and clamped on the travelling microscope stage of KAYSER'S measuring machine, the pitch of whose screw is $\frac{1}{3}$ millim. The stage is moved by turning the screw until the vertical wires in the eye-piece are on the point where a streamer intersects a line of the ruling, and the reading of the screw head then recorded. Thus the ruling gives the y readings, and the screw the x readings.

The x readings have to be corrected for the curvature of the spectral lines which is introduced by the use of prisms.

It is necessary that the spectral lines and the vertical wires in the eye-piece should both be at right angles to the direction of travel of the stage, and the lines of the ruling parallel to this direction. Since the lines in the stationary photograph are finer than the air lines in the rotating one, the adjustments are first carried out by means of the stationary photograph. The photograph is clamped to the ruling with spectrum parallel to the lines of the ruling. The whole is then adjusted on the stage until a point in the eye-piece remains on a line of the ruling as the screw turns. The ruling and the spectrum are then parallel to the direction in which the microscope stage travels and the spectral lines at right angles to it. The wires in the eye-piece

are then rotated until they pass through the ends of a fine spectral line. A rotating photograph being substituted for the stationary one and the lines of the ruling again set parallel to the direction of travel of the microscope stage, readings can now be made. Adjusting by means of the stationary photograph also possesses the advantage that it is not necessary to assume that the air lines appear simultaneously at the top and bottom of the spectrum.

Latterly the velocities have been obtained by taking enlargements (about 10 times) on bromide paper of the negatives and measuring these with the millimeter scale. The accuracy with which this can be done is, except for short lines indicating a large velocity, not so great as the error of experiment. Moreover, more detail can be seen in the enlargements than in the microscope even when using small powers, and the measurements can be made more rapidly.

Accurate measurements of wave-length are not required, the finer air lines and a few well-known metallic lines were used to draw a dispersion curve from which any line could be identified. Measurements of the distances of the metallic lines from the air lines have, however, been made on the stationary photographs for comparison with the moving.

5. *The Photographs.*—In most cases the photographs have been taken in the following manner. A spark was made with the film stationary. The motor having been started, the handle of the Wimshurst was turned by an assistant until about six sparks had passed. The interval between successive sparks would be about a quarter of a minute. Occasionally the stationary photograph was taken last.

In all the photographs reproduced in the plates, the spark length was 8 millims., the upper electrode being the initially positive one. In each case the capacity of the circuit was 0·0306 mfd., and the self-induction that of the leads, the period of the oscillations being $3 \cdot 8 \times 10^{-6}$ second. The speeds of the film at the centre of the spectrum were about 90 metres per second.

It was soon found that the most regular structure in the moving photograph was given by the lead lines λλ 4387, 4245, and the bismuth line λ 4260. The lead spectrum photographed on the moving film is shown enlarged about six times in Plate 28, fig. 2, and the bismuth spectrum in Plate 28, fig. 4, together with the photographs on the stationary film.

There is a slight loss in the definition of the air lines in the moving photographs due to a broadening caused by the air particles remaining luminous for a short time. The air lines shoot straight across the spark gap, whilst the metallic lines are obliquely inclined at each electrode. The inclination of the metallic lines indicates the velocity with which the particles of metallic vapour travel away from the electrodes. The discharge is oscillating, the period of the oscillations being large enough for them to be separated in the photograph.

Let us examine in detail the photograph of the two lead lines, λλ 4387, 4245, shown enlarged about ten times in Plate 29, fig. 5. It is noticed that the streamers start

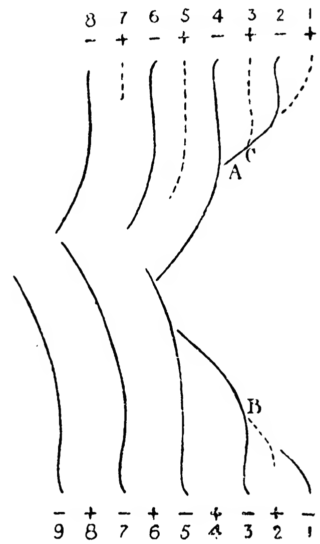
alternately at the top and bottom of the spectrum. However, in the case of the intense short lines of the spectrum there generally appear, in addition to these, fainter streamers, which are simultaneous with the strong ones at the opposite electrode; the faint streamers rarely appear in the two lead lines shown and long lines in general. By comparing the positions of the commencements of the streamers relative to the air lines with the positions of the spectral lines in the stationary photograph we can measure the time from the passage of the air discharge when the streamers start, and find the sign of the potential of the electrode from which they start if we know the polarity of the electrodes before the spark passes. It is found that the first streamer starts at both electrodes practically simultaneously with the air lines. The intense streamers come from the electrodes when negative, and those coming from the electrodes when the potential is positive are faint or absent, except for the first streamer from the initially positive electrode, which is always quite strong.

SCHUSTER and HEMSALECH discovered that all lines of the same spectrum did not indicate the same velocity. The measurements show that there are, as a rule, two velocities. The long spark lines form one class having the smaller velocity, the short lines comprising the second class with the greater velocity. Only in the case of mercury is the line with greater velocity a long one.

Let us examine a typical case of a line of the first class, *e.g.* λλ 4387, 4245 of the lead spectrum, and λ 4260 of the bismuth spectrum shown in Plate 29, fig. 6. Consider only the streamers from one electrode. The first streamer does not reach more than about 1 millim. (in the actual spark) towards the middle of the gap, the second reaches farther and the third still farther, and so on until the streamers from the other electrode are met, beyond which they do not as a rule pass. The first streamer is almost vertical at its commencement and becomes more inclined as it extends farther out. The first streamer is followed by another intense streamer from the same electrode when the potential becomes negative (for when the electrode is positive the streamer is either faint or quite invisible), *i.e.*, after a half period if the electrode considered is the initially positive one (the upper electrode in the photographs), or after a whole period if the electrode is the initially negative one. This second streamer begins at the electrode and is practically vertical throughout its length until it overtakes the first streamer, when it bends over more or less suddenly into a line continuous with the first streamer. The third streamer behaves similarly, bending over when it overtakes the second. In the majority of cases of lead and bismuth photographs the third streamer reaches to the middle of the gap. It is thus seen that the first streamer together with the latter portions of the successive streamers form a kind of envelope reaching from the electrode to the middle of the gap. The fourth and following streamers are similar to their predecessors. A careful examination shows that the streamers after the first have near their bases for a length of about $\frac{1}{4}$ millim. (in the actual spark) a large inclination which would indicate a velocity of about 170 met./sec. and have in this short length become less intense. The streamer

now makes a sharp bend and immediately becomes practically vertical, growing more intense as it advances. We notice that this sudden bend at the commencement of the streamers becomes less pronounced as the order of the streamers increases, and that the inclination of the streamers is becoming less steep than the steep portions of the first three or four.

[*Added, April* 3.—An enlarged drawing of the lead line λ 4386 of fig. 5 is shown in the accompanying figure, the lines representing the first edges of the streamers.



Drawing of λ 4387 (Pb) of fig. 5, Plate 29.

The instantaneous polarity of the electrodes is marked and the streamers from electrodes when positive are shown dotted. The first edges of the 4th and 6th positive streamers are not visible.]

We have also to consider the second class of line, which comprises the short lines of the spectrum. An example is λ 4561 of the bismuth spectrum shown in Plate 29, fig. 7. These lines have a very high velocity, for the first streamer is nearly vertical. Streamers proceed from the electrode both when positive and when negative, although stronger in the latter case. The commencement of the streamers is not bent as was noted in the first class of lines, and the first streamer is never overtaken by a following one. Although the measurements of velocity are most uncertain near the electrodes, yet this greater velocity is real and not due to uncertainty of measurement. On account of the width of the short lines becoming smaller at their tips in the stationary photograph, the readings have been taken on the most intense portion of their streamers; any error due to this cannot be great, for the lines are almost as sharp as in the stationary photograph.

6. *Interpretation of the Envelope.*—We now attempt the problem of finding the velocity of the metallic vapour. So long as the vapour first produced remains luminous it must indicate the velocity with which it is travelling, *i.e.*, the first

streamer throughout its length shows the velocity of the vapour. Before the first streamer has completely died away, having reached only a short distance from the electrodes, it is met by a following streamer. If new vapour has been produced by the oscillation causing this streamer, it will, like the metal first vaporised, indicate, so long as it remains luminous, the velocity with which it is travelling from the electrode where it is produced. Also, unless the metallic vapour has been projected from the electrode, there will be vapour in the space between the electrode and the point to which the material first vaporised has travelled, and it is possible that a pulse of luminosity is propagated through this, *i.e.*, that the particles are successively excited to luminescence without the vapour itself, as a whole, being in motion. A more complete discussion of this phenomenon is postponed to p. 343, but what here concerns us is that if this luminosity is propagated sufficiently rapidly it will reach the vapour produced at the commencement of the spark, which is still leading the way to the centre of the gap. Hence we should expect that when this occurs the streamer will suddenly bend over into line with the previous one and will then indicate the velocity with which the vapour originally produced is travelling. Then, after a further whole period, another streamer, excited by the third oscillation, begins at the electrode, and the same kind of procedure repeated, until when the streamer bends over into a line continuous with the second, the velocity of the vapour produced at the beginning of the spark is again indicated.

Thus we see that the velocity of the vapour in the electric spark is indicated by a kind of envelope consisting of the whole of the first streamer and of the latter portions of the following streamers until the middle of the gap is reached. What the photographs reproduced in this paper show to consist of an envelope was the line measured by SCHUSTER and HEMSALECH. SCHENCK* obtained such an envelope, but did not interpret it in this way.

If the metallic vapour remains luminous much longer than the time for which the oscillation which renders it luminous lasts, the streamers will not be separated in the moving photograph. This occurs apparently in the case of the calcium lines $\lambda\lambda$ 3969 (H), 3934 (K), 3737, 3706, when the spark is produced between poles of calcium metal. This causes the appearance of these lines in the moving photograph to be strikingly different from that of the lead and bismuth lines. Their edge is a sharp, bent line from which the intensity gradually shades off, the streamers being entirely obliterated. In the lead spectrum in which the calcium lines show strongly as an impurity, the streamers are separated and their structure is seen to be similar to that of the lead lines.

The magnesium line λ 4481 is shown in Plate 29, fig. 8, and the mercury lines $\lambda\lambda$ 4358, 4047, 3984, in Plate 29, fig. 9. The mercury was contained in a small cup and the upper electrode was, in this case, lead. The first streamer of the mercury lines is long, and in the cases of the lines $\lambda\lambda$ 4358 and 4047 the following streamers

* SCHENCK, 'Astrophysical Journal,' 14, p. 116 (1901).

have a smaller inclination than the first. The streamers of the lead lines are seen to be shortened and the velocity is smaller.

In Table I. are given the average velocities in metres per second (V) of the various metals in the order of their atomic weights. The lines of type I. are those whose streamers form into an envelope, and type II. comprises the short lines which have a high velocity indicated by the first streamer only.

TABLE I.—Velocities.

Metal.	Lines.	Type of line.	V met./sec.	ρ (H = 1).	$V^2\rho/(64)^2$.
Magnesium . .	4481	I.	460	12	624
Aluminium . .	4530, 4521, 4479	II.	? 870	13·5	2,520
Calcium . . .	3969, 3934, 3737, 3706	I.	416	20	850
Zinc	4925, 4912	I.	388	33	1,200
Cadmium . . .	4416	I.	404	56	2,240
Tin	4586, 4216, 3908, 3861, 3745	II.	? 1370	60	27,400
Antimony . .	4693, 4592, 4352, 4265	II.	? 2230	60	80,000
Mercury . .	4358, 4047		936	100	21,500
	3984		1155		32,700
	4358, 4047 } from Cd amalgam		532		
	3984 } (78 per cent. Hg)		633		
Lead . . .	4387, 4245	I.	303	103	2,325
	4798, 4761, 3854	II.	1960		98,000
Bismuth . .	4302, 4260, 4079, 3864, 3793	I.	283	104	2,045
	4798, 4751, 4561, 3696, 3614	II.	2024		104,500

The effect of electric intensity on the velocity of the metallic vapour has been investigated by varying the capacity. A discharging key was introduced into the circuit and the spark made to pass by pressing the key when the Wimshurst had been rotated a certain number of times. In this way only the spark voltage was altered. The results are given in Table II. for different spark lengths. Whilst the variation of velocity is slight, the tendency is that the velocity increases with diminishing capacity, *i.e.*, with increasing voltage. SCHUSTER and HEMSALECH found the same tendency.

TABLE II.—Effect of Capacity on the Velocity.

Bismuth.

Length of gap.	Capacity = 0·0306 mfd.	= 0·0206 mfd.	= 0·0103 mfd.
centims.			
0·5	V = 295	= 340	—
0·8	283	316	= ? 457
1·2	317	? 496	332

The effect of self-induction has been found by lengthening and shortening the leads from the condensers to the spark electrodes. The results are given in Table III. In the first case the leads were as short as possible.

TABLE III.—Effect of Self-Induction on the Velocity.

Bismuth. Capacity = 0·03 mfds.

Length of gap.	Period = $2 \cdot 82 \times 10^{-6}$ sec.	= $3 \cdot 88 \times 10^{-6}$ sec.	= $4 \cdot 98 \times 10^{-6}$ sec.
centim. 0·8	V = 242	= 283	= 288

7. *Constitution of the Spark.*

(*a*) *Origin of the Velocity.*—We now proceed to discuss the problem of the constitution of the electric spark, and deal first with the propagation of the vapour into the spark gap. We have the following possibilities:—

(1) That the vapour diffuses towards the centre of the gap by the pressure suddenly developed at the electrodes.
(2) That the particles of vapour are charged and move under the action of the electrical field.
(3) That the particles are projected towards the centre.

The velocity of diffusion (or effusion) of the metallic vapour will be proportional to the molecular speed and independent of the amount of matter vaporised; indeed, the velocity will, if there is no loss of energy in eddy currents, by cooling or by internal friction, and if the pressure developed is sufficiently great, be identical with the velocity of sound in the vapour, as has been verified in effusion experiments. This is given in metres per second by the relation

$$V = 64 (T/\rho)^{1/2},$$

where T is the absolute temperature of the vapour and ρ its density compared with that of hydrogen, if we neglect the ratio of the specific heats. Assuming that the temperature of the vapour is not very different in different sparks, we should expect that the velocity of the vapour would be inversely proportional to the square root of the density. In the last column of Table I. are given the values of T calculated from this equation on the assumption that the metallic vapours are monatomic. The high values for lines of type II. show that the velocity of the particles emitting these lines is due to some other cause than diffusion.

That the velocity is due to diffusion is certainly the simplest explanation of the phenomenon, and diffusion must, in any case, play a great part. It was not to be

expected that the velocity of the vapour in the spark should be anything but approximately inversely proportional to the square root of the vapour density, for the disturbing influences may be considerable. Eddy currents of considerable magnitude apparently take place, as seen from the irregularities not only of the structure of the spectral lines but also of the "aureole" in the photograph of the spark itself. Since the vapour does not flow into vacuous space,* the velocity of the vapour will be retarded, though it is difficult to estimate the magnitude of this effect. The experiments on effusion show that the velocity does not fall appreciably until the back pressure approaches one-half that causing the effusion. However, if we increase this forward pressure by increasing the amount of matter vaporised, we shall reduce the effect of back pressure, and the velocity will probably, therefore, be dependent on the boiling-point of the metal. Attempts were made to find whether the amount of matter present had any effect on the velocity by introducing a small globule of mercury on one of the electrodes. The globule was small and probably disturbed the electric field, but it was seen that the velocity was 125 met./sec., compared with 936 met./sec. when a cup of mercury formed the electrode. The amount of matter vaporised is probably least for metals of high boiling-points, and the order of boiling-points is found to be approximately the reverse of that of velocities.

A second hypothesis is that the particles of vapour are charged. It is well known† that the resistance of the spark varies with the material of the electrodes between which the spark passes. We must, therefore, suppose that the metallic particles are participating in the carrying of the current, *i.e.*, that the vapour is ionised, or that the quantity of air which is ionised varies with the material of the electrodes. The period of the oscillations depends on the resistance of the circuit, and a change in the resistance should produce a corresponding change in the period. The periods for different electrodes are given in the following table; all lines in the same spectrum show the same period:—

Magnesium	$3 \cdot 70 \times 10^{-6}$ sec.	Antimony	$3 \cdot 76 \times 10^{-6}$ sec.
Aluminium	$3 \cdot 89$	Mercury	$3 \cdot 88$
Cadmium	$3 \cdot 74$	Lead	$3 \cdot 84$
Tin	$3 \cdot 73$	Bismuth	$3 \cdot 88$

It cannot, therefore, be said with certainty that the period varies with the material of the electrode.

Now, if the metallic vapour is ionised, then, as the direction of the electric field between the electrodes alternates, the vapour should be alternately impelled in one direction during one half of the period and in the opposite direction during the second half. There might be some lag of the reversal of the velocity behind the reversal of the field, for the kinetic energy already generated by the previous oscillation would

* There will be a partial vacuum due to the sound-wave.

† FLEMING, "Principles of Electric-wave Telegraphy."

first have to be destroyed. No such change in the direction of motion of the vapour has been found in the streamers. In some cases, however, the envelope is not straight, but sinuous; where one streamer overtakes the previous one and falls into the envelope it indicates a higher velocity than the end of the previous streamer, and afterwards has a smaller velocity. This sinuosity is noticed in several photographs, but in the majority the envelope is straight. The acceleration and retardation of the vapour is coincident with the alternations in the field, but the retardation is not sufficient to reverse the direction of motion. The photographs show that the charge of the particles is negative. The successive alternations in velocity are 550, 130, 670, 190, 460 met./sec., the variation becoming smaller as the oscillations are dying out and as the vapour approaches the centre of the gap.

Unless discretion is used in selecting the point whose co-ordinates are measured, such variation in the velocity might be introduced where none exists. If a streamer does not actually run into the one following, there might be a tendency to take a reading on the steep part of the latter, which does not indicate the velocity of the vapour.

This sinuosity apparently would indicate that sometimes the metallic vapour is ionised. However, the action of the electrical field on charged particles cannot be the sole cause of the motion of the metallic vapour, for, owing to the reversal of the electrical field, the mean velocity during several periods would be small.

And, lastly, there is no evidence to support the hypothesis that the vapour is projected with the required velocity from the electrode.

It is, perhaps, fortunate that in any spectrum only two velocities are obtained. More than two would be difficult to explain. According to the simplest conception, viz., that we are dealing with a case of diffusion, the velocity would be inversely proportional to the square root of the vapour density, and it would seem simplest to suppose that the vapour which gives rise to the second class of line is more highly dissociated than that emitting the first class. If this is the case we must have, that if the vapour emitting the short lines of the bismuth spectrum is monatomic, that emitting the long lines contains five atoms to the molecule, which is very improbable. The impossible values obtained for the temperature of the vapour show that the velocity of the second class of line is not due to diffusion.

Another explanation might be that the short lines are emitted by charged molecules which are impelled with high velocity by the electric field, whilst the long lines are due to non-ionised vapour.

(*b*) *Propagation of Luminosity through the Vapour.*—Since we are most probably dealing with the diffusion of vapour from the electrodes, there will be vapour present in the space between the electrode and as far as the vapour starting at the first oscillation has reached. The electric current which is re-established in each oscillation can raise this vapour again to incandescence, and a streamer thus be produced. Where this streamer will start, whether at the electrode where there is always most

vapour, or somewhere in the middle of the spark gap, does not appear at first sight from these considerations. The photographs show, however, that generally the vapour at the electrode becomes luminous first, but occasionally the luminosity is propagated also from a point within the gap both towards the centre of the gap and towards the electrode. The average velocity with which the luminosity is propagated through the vapour of bismuth has been found to be 800 met./sec. for λ 4260 and 2200 met./sec. for λ 4561. In the case of mercury the velocity of the vapour is larger than the velocity of propagation of luminosity through the vapour.

The luminosity which produces those portions of the streamers not forming part of the envelope is probably propagated in a manner similar to that of the luminosity of the air. In the moving photographs the air lines are not inclined sufficiently to be measurable. But this does not mean that the air molecules are moving with an exceedingly high velocity, and we should not expect a Doppler effect commensurate with such a velocity, for the air rendered luminous in the middle of the gap probably has not come from the electrodes. So in the atmosphere of metallic vapour in which streamers may be produced by the oscillations of the discharge we should expect to find streamers which are not due to a velocity of particles, and which will probably be steep.

8. *Duration of the Luminosity.*—The air lines are slightly broadened in the moving photographs. The amount of broadening shows that in $6{\cdot}9 \times 10^{-7}$ second the intensity has become insufficient to affect the photographic film. SCHUSTER and HEMSALECH found that the air line λ 3995 was thinner near the electrodes than in the centre of the spark. Now the air lines are generally fainter at the electrodes, and the apparent broadening of λ 3995 is seen to be due, at any rate in part, to two faint air lines near it, generally distinguishable in the moving photograph, but which at the electrodes are too faint to appear.

Stationary photographs measure the total amount of light falling on the plate whilst the spark is passing. Whether a line appears or not in the moving photograph depends not only on the intensity of the light, but also on the length of time for which the luminosity endures. Thus a line of short duration may be visible on the photograph when a line equally strong on the stationary, but of longer duration, may disappear. From their relative intensities in the moving photographs it is found that lines in the spark which also occur in the arc are of greater duration than the spark lines, and that the longer the line the greater is its duration, the short lines appearing also much sharper and finer than the long lines. It may be noted that SCHENCK, who measured the interval between the times when a line first appeared and when it last appeared, found this interval greater for the arc than for the spark lines.

9. *Summary of Conclusions.*

1. The velocity of the metal vapour is given by inclination of an envelope formed by the meeting of the first few streamers.

2. All lines of the same spectrum do not indicate the same velocity. They may be divided into two classes :—

(i.) Long lines, indicating the normal velocity ;
(ii.) Short lines, indicating a greater velocity.

3. The velocity is greatest near the electrodes, and falls away to a nearly uniform velocity.

4. The velocity of lines of type I. is probably due to diffusion ; that of type II. and of the mercury lines is too large to be explained in this way.

5. The envelope indicating the velocity of the vapour is occasionally sinuous, indicating that the particles are in these cases charged.

6. The velocity varies little with the spark voltage or with the self-induction of the circuit.

7. The velocity is apparently dependent on the amount of matter vaporised, and is, generally speaking, less for a metal of higher boiling-point.

8. The luminosities of the streamers of the short or "spark" lines are of shorter duration than those of the long or "arc" lines.

9. The streamers start at both electrodes, but are stronger when the electrode is negative, except the first streamer from the initially positive electrode. The streamers from the positive electrode are but rarely seen in the lines of longer duration.*

10. The period of the circuit is practically independent of the material of the electrodes.

My best thanks are due to Professor SCHUSTER for his interest throughout the research and for many valuable suggestions ; also to Professor RUTHERFORD and the staff of the laboratory for numerous suggestions. I have been indebted to Mr. C. RILEY, B.Sc., for his careful assistance in making the experiments and measuring the photographs.

[**April* 3.—In the paper as originally presented this sentence ran as follows :—"The streamers from the positive electrode are only seen in the lines of short duration."]

ADDENDUM.

[*Note added April* 3.—The drawing reproduced on p. 338 *supra* has been prepared at the suggestion of one of the referees, and shows, with all the clearness of the original negative, the first edge of each streamer of λ 4387 in fig. 5 (Plate 29), which contains few accidental irregularities.

The referee suggests that the positive streamers are curved and the negative ones straight, this explanation bringing the phenomena of the spark more into line with those of the arc.

The presence of positive streamers in the long lines is exceptional, but in all cases the edge of what I have considered as one negative streamer forms a perfectly continuous line throughout its length. In several photographs instances occur where the positive streamer runs side by side with the negative (*e.g.*, in λ 4387 of fig. 5, the 5th + and 6th − at the upper electrode), the bend in the negative streamer taking place before the positive has met it.

If we are dealing with one of the negative streamers which fuse together into an envelope, *i.e.*, in which the streamer has again raised to incandescence the vapour produced at the commencement of the spark, the streamer ceases to be a pulse of luminosity on overtaking this vapour which is leading the way to the middle of the spark gap and must become inclined, since the vapour is travelling slower than the pulse of luminosity. It therefore seems to me to be not the simplest explanation to ascribe this inclination to a positive streamer previously almost invisible.

In those later pulses of luminosity which do not overtake the diffusing vapour it would be difficult to explain why the pulse from the negative should stop dead in the middle of the vapour at a distance shorter than that to which previous pulses have extended, and how the positive pulse, previously faint or invisible, should at this instant burst into intense luminescence.

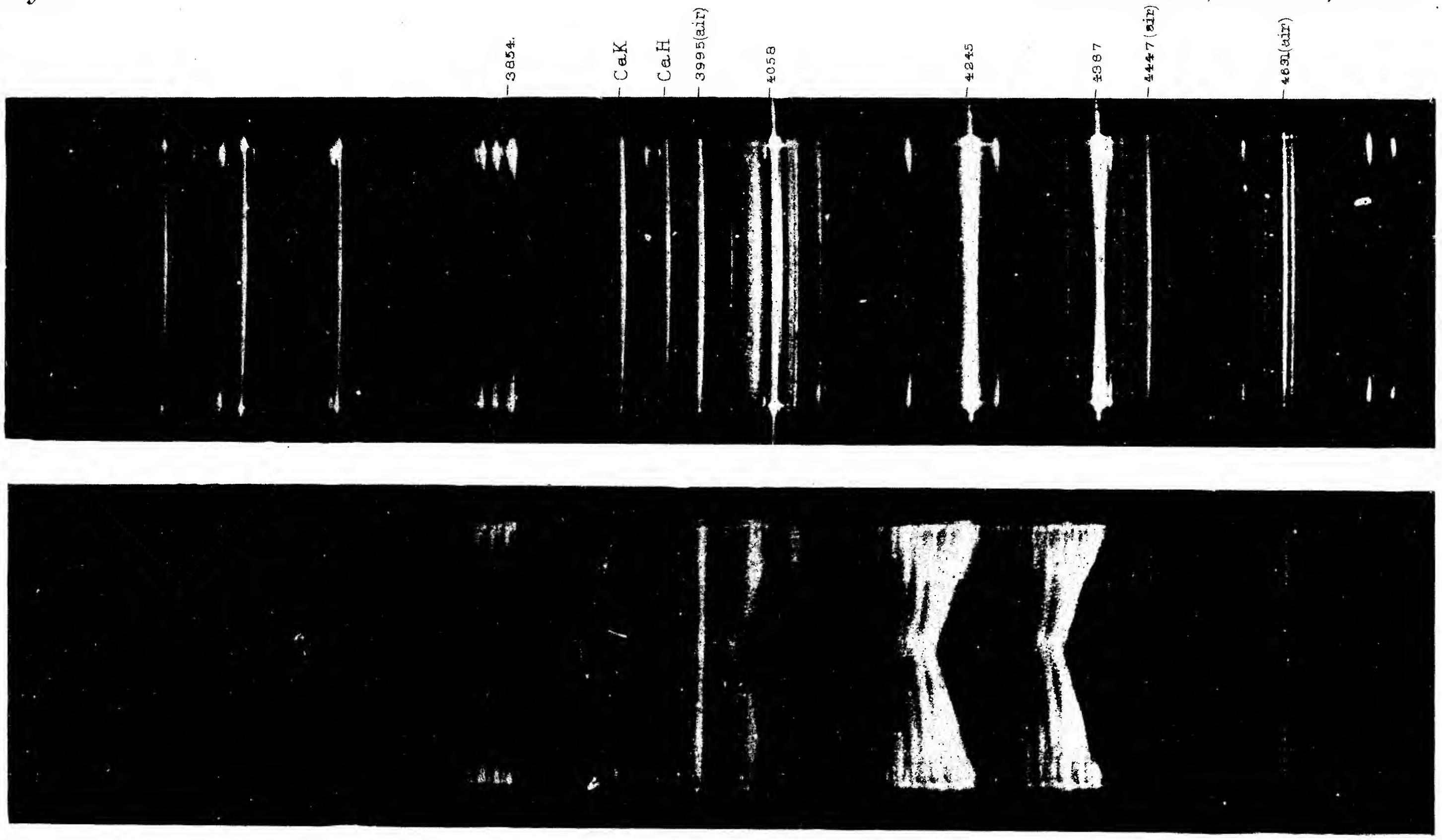
As regards the sinuosity of the envelope, the points of discontinuity are where the streamer meets the negative streamer and not the positive, as the referee's suggestion requires, *e.g.*, at the points in the drawing marked A and B, but not at C. My present opinion is that the cause of the sinuosity is the alternation in the temperature of the metallic vapour.

The crossing point of the two envelopes in fig. 5 is very slightly nearer the upper electrode (2 millims. in an enlargement in which the width of the spectrum is 68 millims.), but this is by no means a rule; in general the inclination of the envelopes is the same at the two electrodes.

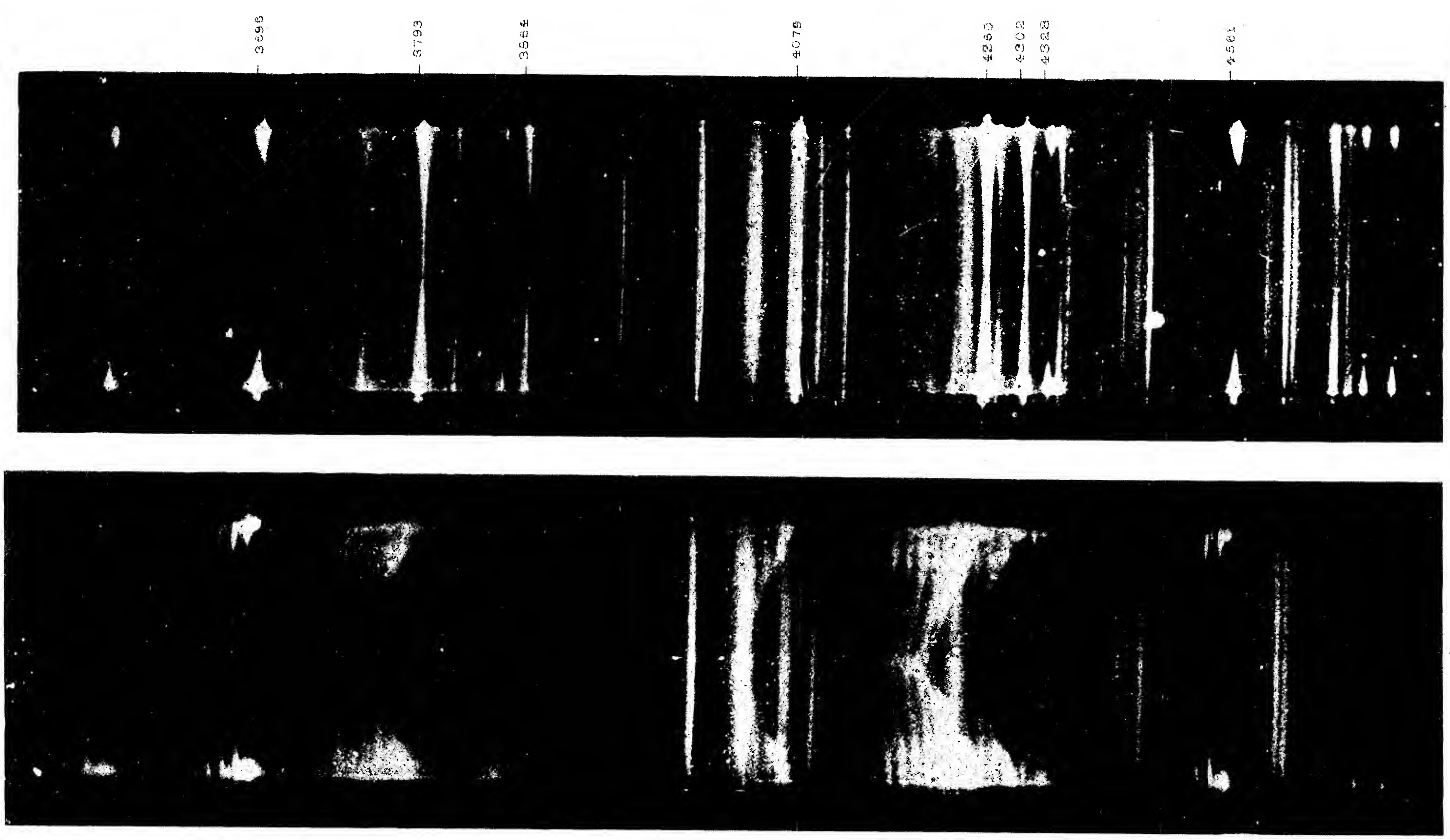
Photographs have already been taken with larger self-induction, but they do not give any information on the point, for the streamers die out before the following ones overtake them.

It is to be observed that the spark described by HEMSALECH in 'Comptes Rendus,' 142, 1511 (1906), was produced under very different conditions from mine, and that in it the negative luminosity did not travel into the spark gap. WALTER, in 'Ann. d. Phys.,' 21, 223 (1906), and SCHENCK, in 'Astrophys. Jour.,' 14, 116 (1901), find that the streamers come from the negative electrode, and the former seeks to explain it as due to kathode disintegration.

It would be an important acquisition to our knowledge if our views of the phenomena in the electric arc could be found to apply also to the spark, but I do not think that the photographs support the suggestion.]



Figs. 1 and 2, Lead.



Figs. 3 and 4, Bismuth.

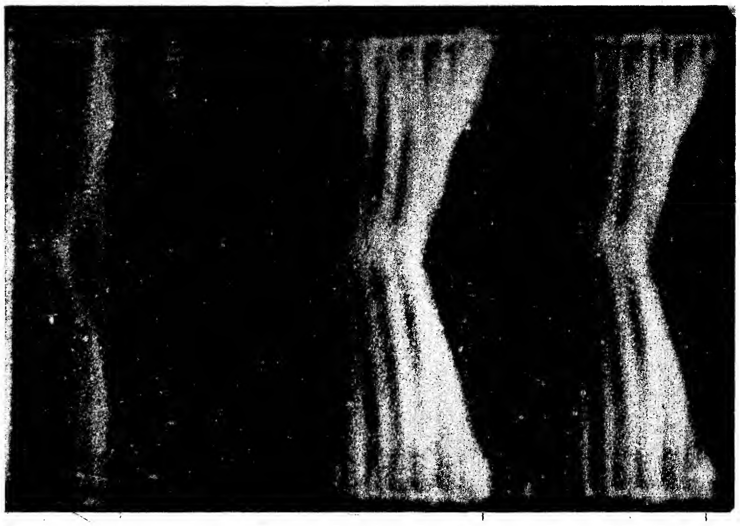


Fig. 5, Lead.

Fig. 8, Magnesium.

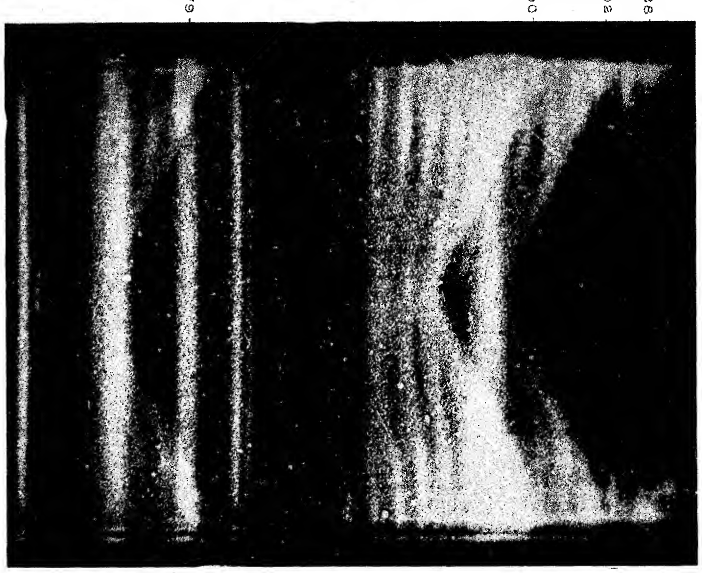
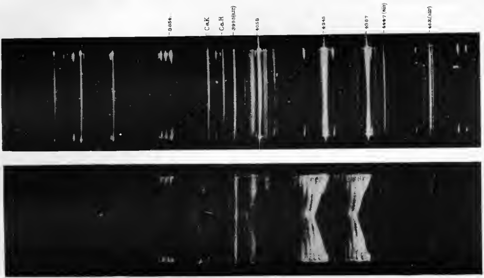


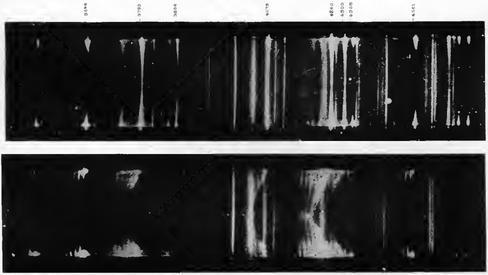
Fig. 6, Bismuth.

Fig. 7. Bismuth.

Fig. 9, Upper electrode Lead, lower electrode Mercury.



Figs. 1 and 2, Lead.



Figs. 3 and 4, Bismuth.

Fig. 5, Lead.

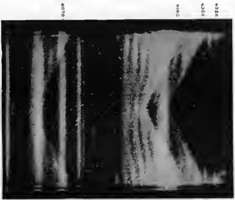


Fig. 6, Bismuth.

Fig. 7.
Bismuth.

Fig. 8, Magnesium

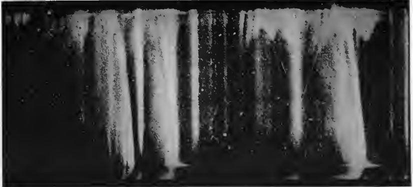


Fig. 9, Upper electrode Lead, lower electrode Mercury.